# Small Transmitting Loop Project

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## Introduction

Of the many different antenna projects I have built for HF, the most interesting and rewarding project was the small transmitting loop. After consulting many of the available Internet sources, and by combining ideas, I was able to assemble an antenna that performed well, even under poor band conditions. The experience was so much fun that I built several different ones.

## Thinking About Loops

Having spent several years as an apartment dweller before moving here, I have a keen sense of how difficult it is to do effective HF communications from restricted spaces. I have always wanted to build a small loop, and I recently decided that it was time to try.

I have also been intrigued by the work of some amateurs who have suggested that small loop efficiency and effectiveness can actually be far better than conventional wisdom might suggest. Among these are G3LHZ, who has done some interesting experiments trying to account for the losses predicted by the traditional loop antenna theory. I was rather inspired by the fact that his experiments to date have not been able to account for *all* of the energy that the theory says should be lost to heat. More about this later.

What follows is a walk-through of my experiences building loops. I'm not going to include the spreadsheets, calculations, theoretical formulae, etc. I will include links to the more interesting ones at the bottom of the article. What I want to capture here are the more practical experiences, and some of the "Ah ha!" moments of the project.

## **Version 1** - Just the Essentials

I didn't want to get a lot of cash tied up in an experimental antenna until I was convinced that the principles were sound, and that I could make them work for me. People who use small loops often make impressive claims about their performance, but then again, everyone's baby is beautiful to them, right?

Since finding a quality tuning capacitor is the most difficult step in procuring materials, I started with that. I had quite a bit of success using open-wire feed line for feeding and matching my dipole, and I knew that the voltage handling capacity of such line is quite high. This line is also very cheap.

So I settled on a basic and minimal small loop, 3' in diameter, using a stub made from quality window line as the tuning capacitor. This way I could just toss the antenna if it didn't work well, without tossing a lot of money. A 100' roll of 300-ohm window line is around $20.

The first loop was tuned for a single frequency, 14,070kHz. I thought digital modes would be a good way to test the antenna, especially since so much digital activity is clustered tightly around a single PSK-31 frequency on each band.

In keeping with my cheap approach to my experimental antenna, the first mast was made from PVC plumbing pipe. It is non-conductive, and the large-bore PVC pipe is very rigid at short lengths. I keep a surveyor's tripod handy for doing antenna experiments, so between that and the PVC, I had the materials to build the support.

The tripod will accept a PVC pipe of about 1-1/4" so that was the size chosen for the mast. 5' lengths are commonly available, threaded connectors were used to to join the loop's 5' section with a second 5' section that would slide into the tripod. This allowed a 10' overall height, that could be easily assembled and disassembled.

Some things I learned about using PVC as a mast:

- Conveniently, 1" PVC pipe fits very nicely within 1-1/4" PVC pipe. If you cement the two together, one inside the other, the strength and rigidity of the mast increases substantially. Most of the loops shown here use this arrangement in at least some part of the mast and/or support.
- When using the threaded connectors, it is very wise to apply a small amount (or not-so-small amount) of dielectric (silicone) grease to the threads before trying to mate them. Remember, this is plumbing pipe, and the various connectors are not meant to be disassembled repeatedly. They are meant to glue together and stay glued <u>for decades</u>. The threaded connectors I used had a slight taper, which means they were also meant to thread together tightly, and stay that way. Without some kind of lubricant to prevent this, I would eventually need some large wrenches to twist them back apart.
- Using a high-quality cement to join the pipe to the connectors is a must. Few things will ruin your day faster than watching your beautiful antenna creation come crashing to the ground because a joint worked loose. Cement is cheap. Rebuilding an antenna is not.
- The tripod is a great way to support the antenna, but loop antennas can get very top-heavy. The tripod will easily support the bottom mast by itself. Before threading the loop itself onto the bottom mast section, I made sure to guy the bottom mast section just above the tripod. This is absolutely mandatory. More than once, I had to catch a falling loop because the wind had caught it just right, and caused it to tip over. The tripod wasn't enough to resist the leaning tendencies of the loops under wind load, even though the entire thing was only 10' above ground.
- The green guy lines in the pictures are relatively thick nylon rope. Nylon is not typically UV-resistant, so using it as a long-term guy line for a permanent installation is probably not a good idea. There <u>are</u> inexpensive ropes available that are meant to be used as guy lines for permanent antenna installations, and these ropes are UV-resistant. If you use nylon outside for long periods of time, the sun will eventually make it brittle to the point of failure.
- Speaking of guys, I used cheap aluminum guy anchors from Wal-Mart. These are basically tent stakes, and were more than adequate to hold the long guys in place. However, there is also a stake in the ground that you cannot see in the photographs. It is directly inside the bottom support PVC pipe segment. This keeps the bottom of the mast from sliding around on the ground. This is also mandatory, because of the top-heavy nature of the loop. Without it, the bottom mast segment could shift, and send the antenna falling.

For the loop itself, I chose 5/8" soft copper tubing. This is the type you might use to feed refrigerant to an air conditioner. It is often sold as "refrigeration tubing." The small-loop theory says that larger bore tubing makes the antenna more efficient, but 5/8" seems to be a nice compromise size, and is still in the "cheaper" grade of tubing. Price starts to climb rapidly as you increase in tubing size, and again, I was just trying to prove the theory.

Soft copper tubing also lends itself to being easily formed into a circular loop. Unlike loops built from copper pipe, the tubing doesn't have to be cut and joined with elbows. Having a long continuous piece of copper, circular shaped, seemed ideal for keeping losses low. After all, solder joints increase losses. I have seen some very clever jigs for doing circular bends of piping. I did mine by hand, and the result was almost as good. The trick is to bend the tubing a little at a time, working your way around the length of tubing several times, making very small bends every few inches during each pass. Out of the box, the tubing is already coiled up in a nice circular shape. All you have to do is increase the radius of curvature to get it to the diameter that you want.

For the inner (driven) loop, I chose 1/4" soft copper tubing. An SO-239 connector from Radio Shack was carefully soldered to the ends of the inner loop.

Both types of tubing can be purchased by the foot from local hardware shops for reasonable amounts. I was able to secure both from Lowe's for just over $1/foot.

Some notes about working with copper tubing:

1. Handling copper with your bare hands will very quickly cause it to tarnish. The copper content of pipe and tubing is extremely high, and copper loves to react to the natural oils and salts from your skin. If you will wear thin latex gloves while handling the tubing, and especially while bending it, the copper will retain its shiny appearance and you will minimize contaminants on the surface of the inductor.
2. On the subject of contaminants, remember that the thickness of the copper is irrelevant for an antenna. The skin effect of RF flowing on any conductor will force all of the current into the top few micrometers of the copper tubing. I have not seen any literature that describes how tarnish, oxidation, and other surface contaminants effect the RF resistance of a conductor, but the cleaner you can keep the surface, the better.
3. It is easy to polish the copper loops with a wire wheel, available at any store that sells drills and bits. The coarseness is up to you, but mechanically polishing the imperfections out of the loop is easy and well-advised. If you use a drill or Dremel to work on any part of your loop, <u>make **sure** to wear eye protection</u>.

Now it was time to tune it.

To figure out how long to make the capacitor stub, I used some existing 300-ohm stubs cut for the dipole project.  These were in lengths ranging from 6" to 8', in binary increments.  I can combine these into any length of stub, to a resolution of 6".  To interconnect them, I soldered PowerPole connectors to the ends.  In a very handy coincidence, the spacing between PowerPole contacts is almost exactly the same as the spacing between the wires of 300-ohm window line.  This way the stubs could be connected in series quite easily.  At the top of the loop, where the copper tubing is split, I soldered in a 2" stub with a PowerPole connector, for attaching to the stub of the stub.

Some thoughts about capacitive stubs:

- Using feedline stubs for matching isn't a new idea. People have used open-wire and coaxial feeder stubs for impedance matching purposes for some time. The dipole matching project used both series and shunt stubs between the coax and a 600-ohm feedline to match the two, and was inspired by W5DXP's work on that very subject. His project used series transformer sections exclusively. I just extended the idea by adding a second piece of feedline, open-ended, as a shunt section on the high-impedance side, to further refine the match. That piece served (mostly) as a matching capacitor of very small value. That is the idea here, with the loop. The stub is open-ended, and serves only as a capacitor.
- From an efficiency standpoint, the stub isn't a good permanent solution, because it adds more than capacitance. It serves as a delay line that also contains a non-negligible amount of inductance, that actually adds to the effective length of the large copper loop. For use as a first experimental capacitor it was a wonderful and cheap way to do tests. In the long run, a good design will probably use some kind of lumped-C capacitor, such as a vacuum-variable or an air-variable.
- I have seen some really nice designs for homebrew trombone-style capacitors made out of copper pipe (not tubing). I opted to avoid these as a final solution for two reasons.
    1. I wanted to operate high-power levels. This means that the dielectric of the capacitor needed to be high-quality and low-loss. A vacuum is hard to beat for this purpose.
    2. I'm not yet convinced either way with respect to how much additional inductance is introduced by the trombone arms. It may be negligible, but as with the window-line stub, it certainly "looks" substantial, due to the lengths involved.

After some experimentation, I found the length closest to 14,070kHz for the loop. Using a PalStar analyzer, I mixed stubs until I found a length that was close. I then took a spare stub that only had one connector, and started cutting it from one end about 1/8" at a time, until I slowly resonated the antenna at 14,070kHz.

For the feed loop, I used a single turn of 1/4" tubing, fed directly in a balanced fashion from the coaxial cable. I used an MFJ-915 choke close to the feed point, to ensure that no common mode current flowed on the cable. During later experiments, I found that this is usually not needed, but I didn't want to pollute my test with common mode radiation or reception. I wanted all the power to go into the large loop, whether that mean radiation or loss.

Even before making any contacts, I noticed that the loop Q was quite high. Drifting in frequency more than 15kHz from the center frequency would raise the SWR quickly to 2:1 and beyond. Another 15kHz would take the SWR beyond 10:1, which is the measurement limit of the Palstar device.

Since the high Q is critical to maintaining loop efficiency, I knew I was on the right track. Efficiency and Q are very tightly coupled, and for an electrically small (dare I say, tiny?) antenna, efficiency and Q are directly proportional. Higher Q tends to indicate higher efficiency for a small radiator. If the antenna had a lot of resistive loss, the Q would fall, and the 2:1 bandwidth of the antenna would be wider.

The band conditions on 20m the day of my first tests were terrible, but I still had no problem making coast-to-coast domestic contacts on PSK-31, even in the presence of heavy fade. After spending an afternoon making contacts on the loop, and watching several DX stations come in quite clearly, it was obviously working well enough to justify getting more serious about the loop project.

**Version 2** - Vacuum-Variable Capacitor

The next step in improving the loop was to add a variable capacitor, to allow the antenna's frequency to be changed.  I wanted to use the loop on at least a couple of different bands, to see how the performance changed as the loop wavelength was changed.  A 3' loop is just under 9.5 feet in length.  That's about 1/8 wavelength on 20m, almost 1/4 wavelength on 15m, and well over a quarter wavelength on 10m.

Alan Bond over at MaxGain was able to provide me with a couple of used vacuum variable capacitors, 10-60pF, 10kV, for around $100 each, shipped.  Vacuum variable capacitor prices only go up from there, so I thought that would be a good starting place.  According to the calculators available online, those capacitors would allow me to tune across the frequencies that I cared about, at a peak power level of 500W, which is the limit of my station, anyway.

The capacitor replaced the stub, and I added a shaft made of PVC, to allow for turning the capacitor shaft from the ground.  At left is an image of a driveshaft added to a 5' loop, constructed later.  At right is a close-up of the capacitor mounting.

You will note that I used wires to connect the ends of the inductor to the capacitor. Although this wasn't optimal from the standpoint of keeping resistance low, the Q of the loop remained quite high after this change. More importantly, I could tune the loop to any frequency from 20m through the CW/data portion of 10m.

The wires were soldered to the tubing using standard PC-board solder. I tried silver solder, but my first attempts didn't work out well. Later, I'll describe how I was able to successfully resolder with silver-bearing solder.

While working with this loop, I noticed a few interesting things that the standard literature didn't seem to mention. I have no explanation for why any of these were true, but my experience was consistent across all of the loops built:

1. Adjusting the inner loop for 50-ohm resonance was much easier if I moved it vertically, within the loop plane, rather than rotating it about the mast. All of the literature I read suggested the latter.
2. The proper location of the inner loop for a 50-ohm match was extremely dependent on the loop's surroundings; e.g., its height above ground, whether it was indoors or out, proximity to other objects, etc.
3. The *range* of resonant impedances attainable by moving the inner loop along the mast could also be changed by deforming the inner loop to be oblong, rather than circular. This was another technique suggested by some texts, and it was necessary to get 50-ohm resonant matches when the loop was sited in difficult locations, e.g., indoors.
4. The overall loop was also easier to match to 50-ohms if the inner loop was fed at its top, and not at the bottom.

The first point was very helpful, because simply rotating the inner loop didn't always work. By raising or lowering it on the mast, so that the two loops remained coplanar, I could easily reach a 50-ohm point at resonance, regardless of the location details. When mounted outdoors in the clear, the 50-ohm position of the inner loop was several inches up the mast. When used indoors, the 50-ohm position of the inner loop was near the bottom edge of the outer loop. Here's what the 3' loop looked like adjusted for use outside.

A few QSOs later, it was time to add a motor drive to the capacitor, so that I could remotely tune the loop.

**Version 3** - Motor Driven Capacitor

Robotics is a fairly common hobby today, so finding a motor to move the capacitor shaft was easy. I bought a gearhead motor from a robotics wholesale outlet. The gearhead reduced the RPM of the motor from several hundred RPM, to about 3 RPM. Both the motor and the capacitor had 1/4" shafts, so connecting them required only adapting the PVC driveshaft to them. I found a couple of knobs at Radio Shack that did the trick. They were replacement knobs for audio equipment volume controls. The knobs fit tightly inside the 1/2" pipe, and to the shafts.

High-current antennas such as this are capable of generating huge magnetic fields close to the antenna, so I adopted a rule to help keep my test results as trustworthy as possible. I decided not to run any conductors near the outer loop, where the high loop currents exist. That way, the mutual coupling between the outer loop and other conductors was kept to a minimum. The intent was to keep the antenna's radiation pattern as pure and undistorted as possible. To accomplish this, I did a couple of things that also were not mentioned in any of the small loop literature that I found:

1. The coaxial feedline was mounted in such a way to keep several inches between it and the outer loop. This was done by making a large arc from the feed point, over the main loop, then back to the mast.
2. The motor drive for the capacitor was not mounted close to the capacitor. Instead, a long "driveshaft" was formed with PVC pipe, and used to connect the motor to the capacitor. The driveshaft was long enough to allow the motor to be placed well outside the outer loop.

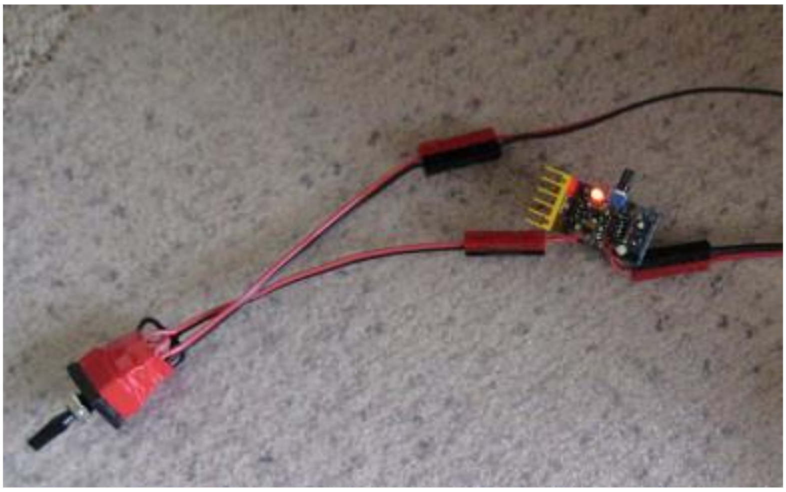
I added a couple of protection items to the motor before using it.  First, I placed a 0.05uF capacitor across the motor's DC terminals.  This keeps the RF out of the motor windings.  Second, I choked the power leads with a common mode snap-on bead, to keep RF from flowing into the motor from the long leads, or back to the power supply from the motor.  The motors also had a vinyl cover added, to weatherproof them.

Another handy tool I borrowed from the robotics hobby was the PWM motor controller.  These devices generate pulses of DC to drive the motor.  Using voltage to control a motor's speed can also be done, but it has some disadvantages:

1. A motor running at a lower voltage develops less torque than one running at full voltage.
2. A motor running at a lower voltage can generate more internal heat, especially since it stalls more easily under load.
3. A motor running at a lower voltage is less efficient than when it runs at its design voltage.

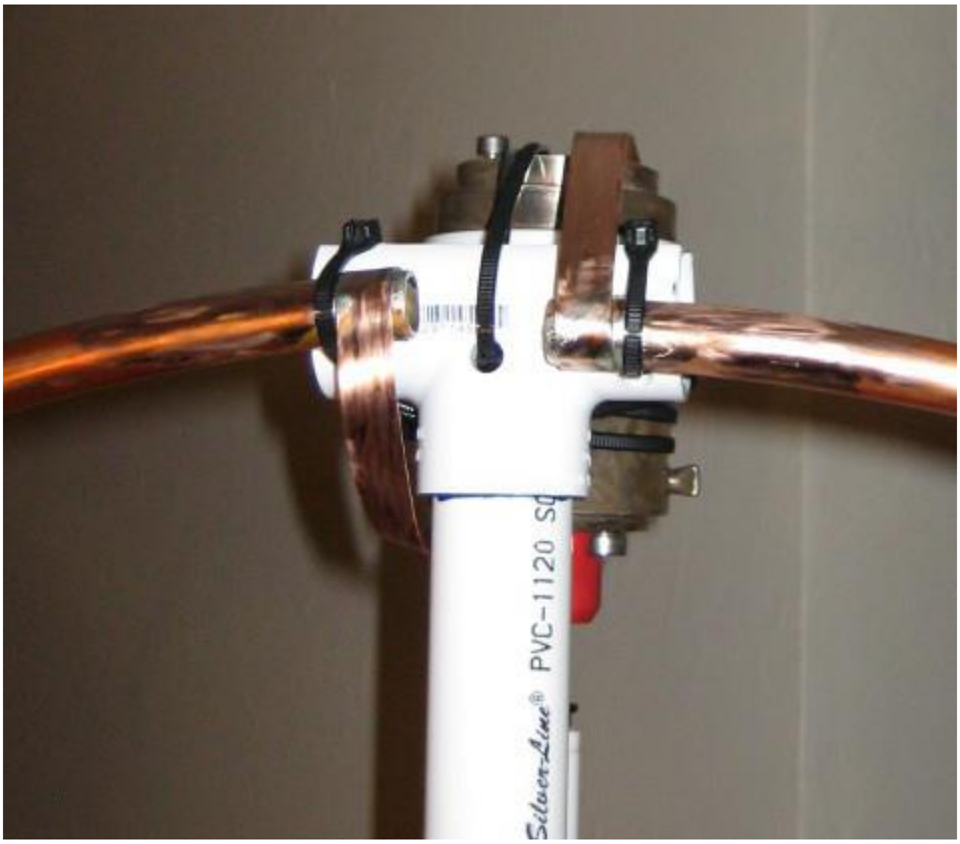
The PWM mostly solves these problems.  By pulsing the power, rather than lowering the voltage, the PWM allows the motor to run at full voltage while moving.  The PWM generator takes advantage of the rotational inertia of the rotor to provide a natural slow-down of its motion, which allows much more fine-grained control over the motor speed.

Adding the PWM to the motor circuit allowed me to more easily find and adjust the resonant frequency of the antenna. I added a DPDT, momentary, center-off switch to the PWM circuit output. This allows me to send normal or inverted voltage pulses to the motor, to rotate it in both directions. Many DC motors are reversible in this way, and the specifications of the motor will tell you for sure. Below is the PWM controller, with the DPDT switch on the output:



The loop was really taking shape, and I was happy with the performance I was getting, but there were still a couple of things I wanted to do to try to squeeze out the last bit of efficiency.

First, I replaced the wire jumpers between the capacitor and the main inductor. Georgia Copper sells nice, polished copper strap in various lengths. I used 1/2-inch strap to make the connections. I also used silver solder the second time. It turns out that my previous attempt failed because I did not properly flux the conductor before applying the solder. Tractor Supply sold me a roll of silver-bearing solder that contained its own flux, and that worked much better.




Note that the copper and solder around the joints was polished after assembly.  This removed the discoloration and oxidation that naturally occurs when using a torch for soldering.  Again, the skin effect of RF flowing on the surface of a conductor adds enough resistance on its own.  I hoped the polish would make sure that the current wasn't flowing through any additional impurities.

Several loop builders also mentioned improvement in performance by adding a fan of short radials underneath the loop on the ground.  I added a set of 15 to 18 radials under the loop, each of which was around 6' long.  These radials are solid copper, THHN-insulated wire.  Next time, I will use stranded wire with short stakes, to make it easier to deploy.

**Radiation Pattern Observations**

The overall loop pattern was nearly omnidirectional. The nulls that I did find were rather sharp. They were, however, enough to null out some RFI from a local neighbor, when the loop was properly rotated. DX contacts were readily made at angles 60-80 degrees from the loop plane. The theory seems to indicate that this is a typical small-loop pattern.

**Bandwidth Observations**

The three-foot loop has a 2:1 SWR bandwidth of **22kHz** on 15m, as measured at the end of a 45' length of RG-213/U.

**More Loops**

In the end, five loops were built. These ranged in size from 5 feet down to 17 inches diameter. Each of the new loops was built to emphasize a particular band. The loop described above was approximately 3' in diameter, and is a good choice for multiband operation from 20m through 10m, with the capacitor chosen.

**20m Loop**

One of the five loops was a 5' model specifically built for 20m performance. It was a larger diameter, making the overall circumference about a foot less than one quarter wavelength at 14,350 kHz. This maximized the efficiency for that band, but still kept it electrically small. Its measured 2:1 SWR bandwidth on 20m is **18kHz**.

This antenna used the second of the two 10-60pF variable capacitors I originally picked up from MGS.  This allowed it to tune well outside the 20m band, but I only used it for this band.  It does tune into the 30m band, but I have not tried to make any contacts there.

**6m Loop**

Back in my college years, 6m FM had some wide-open propagation, and I remember some very nice band openings.  I have been wanting to get back into 6m, but didn't have an antenna that fit well anywhere at the house.  So as an experiment, I also tried a 6m loop.  This loop has a diameter of about 17 inches.  It used a single 3-30pF capacitor for tuning, which was sized to be usable into the 100W range.  This loop has made some domestic contacts, but has not seen a lot of testing yet.

**40m Loop**

Loops that are extremely small electrically are able to maximize other aspects of their operation.  For example, lower noise pickup and deeper nulls.  I built a 40m loop to experiment with these properties.

The loop size was chosen to be approximately 4.5 feet in diameter.  This makes the circumference of the antenna about 11% of the wavelength at 7,000kHz, and the diameter about 3% of the wavelength.  Electrically speaking, that is the definition of "small".

The measured 2:1 SWR bandwidth of the 40m loop is **5.4kHz**.  At this bandwidth, the antenna is still capable of SSB transmission.  However, it reminds me that loops of this size will only be usable for narrow modes (e.g., CW or PSK-31) on lower bands.  Antennas large enough for SSB on lower bands will likely not be easily portable.  This antenna's Q is high enough that it needs frequent retuning while moving up and down the band, even on CW.  It would be difficult to use this antenna in a SSB contest for anything but a "run" antenna.

This loop was a little different than the others, in that I didn't try to use a single capacitor to tune it.  Instead, it used two capacitors arranged in parallel.  The first was a vacuum-fixed capacitor, 100pF, to provide most of the 120pF required to bring the resonant frequency down to around 7,500kHz.  The second capacitor was a smaller 3-30pF vacuum-variable, used to provide the tuning adjustment to pull the frequency down further into the 40m band.

The maximum current rating for the 100pF vacuum-fixed cap was considerably higher than that of the vacuum-variable.  The reason for this is that the current flowing into and out of each capacitor in a parallel arrangement is directly proportional to its value.  When the vacuum-variable is adjusted to 20pF, it shoulders roughly 1/6 of the total circulating current within the loop antenna.  So the current ratings for the two capacitors were chosen accordingly.  This was very helpful, because high-capacity fixed capacitors are far cheaper than high-capacity variables, mostly due to the simplicity of the construction.  By using two caps in parallel, I minimized the cost of the overall capacitor bank considerably.

The initial tests of the 40m loop were very promising.  During a CW contest, the 40m loop made numerous DX contacts in Europe.  When running at 500W, the capacitors showed no signs of heating (SWR drift, physical warmth, etc.).

**10m Loop**

Now that conditions on 10m are improving, a dedicated 10m loop seemed to be a good idea.  Its construction was very similar to the others, and it showed a measured 2:1 SWR bandwidth of**27kHz**.

During a recent 10m contest, I did several A/B tests between the 10m loop and my KIO hexbeam, which is mounted at a height of 23'. The received signal strenth on the loop was about one S-unit less than that of the beam. Given that the difference in expected gain between the two antennas is around 8dB, the signal levels received on the loop were more than satisfactory. The noise level on the loop was also down about one S-unit (6dB). When transmitting, this loop was just as capable of European and domestic contacts as the beam, and I found no stations that could be worked on the beam, but not on the loop.

As you can see in the photo, this loop has been painted with a coat of white enamel. This protects the copper from tarnishing from handling, but it does not seem to have effected the performance in any measurable way. The copper was sanded prior to painting, to make the copper surface as conductive as possible. The other HF loops have been similarly painted, with no adverse effects to performance.

**Next Steps**

Some work still needs to be done before I can just put these out in the yard and leave them as permanent installations.

1. **Security** - Copper theft is all the rage these days. A yard full of copper loops sticking up in the air might be too much temptation for a thief to resist. Finding a way to prevent this may be tough, since the tubing would be easy to cut from the mast. Height is one tool, getting the loop up high enough in the air to make it difficult to reach. Another thought is to paint the copper with a flat enamel that is a dull gray or green color. That would make the antenna harder to see, as well as making it appear to be just another piece of plastic yard junk. A nice side-effect of painting the antennas with an appropriate paint is that it prevents the copper from tarnishing or oxidizing over time, which is particularly helpful with portable antennas like these, that are handled regularly for set-up and tear-down. Keeping the top layer of copper clean is important to maintain high efficiency.
2. **Weatherproofing** - The capacitor needs to be covered and protected from rain, ice, dirt, debris, birds, insects, etc. My initial thought was to invert a trash can, and cut holes in it for the inductor. That doesn't solve all of these concerns, but it's a start. Some kind of sealed plastic enclosure would probably be ideal, especially if the plastic is resistant to UV from the sun. The main reason I haven't done this yet is the number of protrusions that would need accommodation. The enclosure would need holes for the mast, the shaft, and the two inductor ends, at a minimum. The motor also needs some protection, but this is somewhat easier, since the robotics shops offer soft plastic "boots" for most gearhead motors. The boots that I used offer a 90% solution, and I suspect adding a little dielectric grease to the shaft and wire openings would be enough to protect the motor for its lifetime.
3. **Mast Alternatives** - The PVC mast was cheap, simple and effective. However, not all PVC is made to endure the elements. PVC can deteriorate under UV exposure, not to mention the fact that continued flexing of the mast under wind loading will start to weaken it. Rebuilding the loops on a fiberglass mast would be much better, since fiberglass is also non-conductive, but is also tougher and more rigid. I will probably talk to MaxGain about some mast replacements in the future.
4. **Motor Stops** - There needs to be a way to prevent the motor from running the capacitor shaft all the way to either of its physical limits. This could do some damage to the capacitor, but it is more likely to simply lock the rotor of the motor and damage it. For now, I'm just careful, and I use the Palstar analyzer to make sure the position of the capacitor is still well within its limits while tuning.

**An Improved Control System**

I have also done some work on an automated control system for these antennas, and that project is described on the AutoCap Software Page. That article is a continuation of this one, describing control system changes. The software-based controller allowed me to convert the loops to use stepper motors to move the capacitor shafts, and achieve some truly impressive tuning speeds.

That said, the simple DC motors described above are more than adequate for loop control, and are extremely easy to control remotely. The AutoCap software supports both types of motors, and satisfactory results can be had with either one. For the casual operator who likes to rag-chew, a simple gearhead motor with a DPDT switch at the control point makes the loop antenna easier to use than a typical tube amplifier.

**Closing Thoughts** - Possibly Controversial Ones

One aspect of loop performance that I find curious is efficiency. There is some well-accepted classic theory that describes the efficiency of a small transmitting loop. That theory is mentioned in the ARRL Antenna Book, among other places. However, people like

G3LHZ have done some interesting work trying to account for the losses claimed by the classic theory. Strangely, there are real-world thermodynamic experiments that do not seem to support the traditional loss calculations. For example, if a magnetic loop for 2MHz is constructed so that the classic calculation shows a 5% efficiency, and if we feed that antenna with a 100W carrier, we should be able to find 95W of energy (or something close to it) being dissipated as heat somewhere in the loop. Mr. Underhill's experiments using thermal cameras show this may not be the case. When he accounts for the detectable heat generated by the loop, his experiments suggest typical small-loop efficiencies to be on par with other classic antennas, such as dipoles and verticals.

I have spent some time thinking about this discrepancy, and how to account for it within the typical ham homemade loop. This is not to say that I am asserting this as correct, but I believe there are readily-explained reasons why loop efficiency could be far higher than the classic theory predicts.

One simple possibility has to do with construction. Many loop designs, mine included, use open-ended copper tubing for the radiating element. This means that the loop itself actually hastwo conductors, wired in parallel. One is the outside of the loop conductor, and one is the *inside* of the loop conductor. The reason for this is skin effect. Anybody who has run high power RF into a coaxial cable that is poorly matched to a balanced antenna is familiar with the "feedline radiation" effect, and this is exactly the same thing. In this case, The outer and inner surfaces of the loop conductor are connected together at the ends, so the two conductor shells carry current in parallel. Depending on the difference in diameter of the two surfaces, the effective increase in surface area can be almost 100%, roughly doubling the surface area of the main element. *"But the inner conductor is shielded from the environment by the outer conductor,"* someone might object. This is true for the electrical field, but *not* the magnetic field, which just happens to be the largest component of the EM field created by this type of antenna.

Many loop builders unknowingly *depend* on this two-surface behavior, because their designs utilize trombone-style capacitors. These capacitors are often fed current on their outside surface, but the outer "plate" of such a capacitor is actually the *inside* surface of the outer trombone tube.

Another possibility has to do with the pattern of current flow on a loop antenna. At its core, such a device is a capacitor and an inductor, connected back-to-back. You can think of it as a series-resonant circuit, where the capacitor and inductor are in series with the abstract "radiation resistance", which is the "load" presented to any antenna, allowing the RF current in the antenna to be transferred into free space.

We want the "radiation resistance" of any antenna to be much larger than the sum of all other losses. This is the heart of antenna efficiency calculations.

Power transferred into the antenna is going to be dissapted in one of two ways -- radiation into space, or heating of the antenna or its immediate surroundings. The copper loops and the metals in the capacitor contain the real resistive components of the antenna. If heating of the antenna is to occur, it must happen here. In addition to the intrinsic real resistance of the copper itself, we must again consider the skin effect, which effectively "thins" the copper conductors for the purposes of conducitng RF current.

Copper conductors in a magnetic loop antenna are not simple conductors, however. Even when you factor in skin effect, there is still a component missing. All of the copper conductors in a small transmitting loop are part of one of two inductors. The small loop is a primary winding of a two-winding air-core transformer. The large loop is the secondary. The current flowing through these conductors are operating at varying amounts of phase angle from the voltage at any given point. Inductors delay current, capacitors delay voltage. Since all of the metal in the antenna is part of a reactive component, the power flowing in the entire loop is subject to voltage-current phase angle shift.

There are two points in the antenna where the phase angle between voltage and current will be zero. These points would be very difficult to locate physically, but they must exist. The large copper loop is an inductor along its entire length. The capacitor is a lumped reactive component, and its leads are, for all practical purposes, part of the inductor. As current circulates in the loop, the current will experience the highest inductive VAR (volts-amps-reactive, or "reactive" power) value at the bottom of the loop, furthest from the capacitor. The highest capacitive VAR value will be within the capacitor itself. Somewhere along the conductive path between each capacitor plate and the bottom of the loop, the capacitive phase angle will cancel the inductive phase angle, and all of the power at that point will be real (i.e., the impedence is completely real, and has no complex components). Remember these points for the moment.

Heat in a circuit is generated as current passes through real resistance. The reactive components of a resistor do not add to the heat generated. Put another way, current cannot do work (including generating heat) unless a voltage potential is also present. The amount of work that can be done is inversely proportional to the phase angle between the voltage and current. This is the whole idea behind power factor -- the voltage and current must overlap to some level to do work. Power companies rely on this principle, and enforce it vigorously in their customer contracts. So heating of any AC circuit component is directly related to the phase angle of the voltage and current within that component.

Now back to the loop. Remember that there are two "loads" within our antenna. The first is the radiation resistance of the antenna, which is its ability to transfer RF current into radio waves in free space. The second load is the loss inherent within the antenna. Remember also that there are two points in the antenna where voltage and current are in-phase. These are the points where the RF energy is able to do real work and heat the antenna conductors. As we move away from these points, there is some amount of phase angle between voltage and current. This angle diminishes the ability of the RF energy to heat the conductors where the angle is not zero. The closer the angle is to 90°, the less heating can occur. By restricting the zero-VAR area of the antenna to two points, and to a lesser extent, the regions immediately around those points, the resistive losses of the antenna are concentrated around those two points. Despite the fact that RF current flows at high levels throughout the antenna, these two points and their immediate surroundings become the focus for resistive losses.

However, remember that there is a second load in the circuit: the radiation resistance. We can't pin a location on this load, but its value is still part of the efficiency equation. If we rethink the loop, and realize that the heating losses don't occur throughout the entire conductor length, but are instead centered at two points in the loop, that realization leads us to the conclusion that the current theory for small transmitting loops is grossly overestimating the contribution of $I^2R$ losses contributing to the efficiency calculation. This would go a long way to explain Mr. Underhill's experimental results. The ratio of RF energy being dissipated by the radiation resistance to that of the RF energy being dissipated by the resistive losses of the conductors is likely much higher than predicted by the classic theory. I am increasingly convinced that this is due to the reactive nature of the antenna components, as described above.

If we assume that this is correct, then how might this influence the design and construction of loop antennas? How could we squeeze the highest efficiency out of an antenna if we are correct?

A key improvement would be to focus on the two points of minimum phase angle, and minimize the real resistance of the conductor found there. To do this would require being able to calculate these locations. Given a value for the capacitor, and a length of the attached inductor (that included the leads and plates inside the capacitor itself), it should be possible to estimate their location. Given that the capacitor is a lumped value, and the inductor's reactance is distributed over a relatively large length, it is entirely possible that most real heating occurs close to the capacitor body, possibly within the jumpers between the capacitor leads and the main inductor body. This may explain why heating in G3LHZ's loops appeared to be rather uniform within the inductor body. The maximum heating may have been taking place at spot locations on the capacitor jumpers. Since we tend to expect these connections to be "weak spots" anyway, the extra heating there and its cause may have been overlooked.

It is also possible that the heating effect of loop antennas is just not sufficient to make it necessary to find the two main heating points. Even at these two points, the radiation resistance may sufficiently trump the real losses that the real losses are insignificant. This idea is also supported by the experimentally determined efficiencies of Mr. Underhill's loops.

Devising experiments that would support or discredit these ideas is difficult. However, the current experimental evidence has made me curious, and will continue to encourage me to experiment with these antennas.